Quantum antidot as a controllable spin injector and spin filter

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We propose a device based on an antidot embedded in a narrow quantum wire in the edge state regime, that can be used to inject and/or to control spin polarized current. The operational principle of the device is based on the effect of resonant backscattering from one edge state into another through a localized quasi-bound states, combined with the effect of Zeeman splitting of the quasibound states in sufficiently high magnetic field. We outline the device geometry, present detailed quantum-mechanical transport calculation and suggest a possible scheme to test the device performance and functionality.

The most ambitious and challenging long-term aim of semiconductor-based spintronics is the practical implementation of quantum information processing based on the spin properties of the electron. One of the most promising practical realization areas of quantum logic are low dimensional semiconductor structures like quantum dots and related lateral structures defined in a two-dimensional electron gas. Two coupled dots, for example, can serve as the simplest two-qbit quantum gate[1].

There has been several suggestions on how to implement the spin control in quantum dots and related systems[2], and some of the proposed schemes has already demonstrated their potential for injection and detection of spin-polarized current[3]. The spin-polarized injection and detection of the electrons in a quantum dot has recently been demonstrated in the edge state regime[4]. However, in the above experiment no control over the spin state was possible (it was always spin-down spins that were injected into the dot).

In a present paper we propose a new method to control the spin freedom in the edge state regime by making use of an *antidot* embedded in a narrow quantum wire. Based on the proposed device, a spin population can be achieved in a *controlled* way, and the read-out spin information can be converted into transport properties. In the present paper we outline the device geometry, present detailed quantum-mechanical transport calculation and suggest a possible scheme to test the device performance and functionality.

Quantum antidot is a potential hill defined in 2DEG by means of e.g. electrostatic split gates[5,6,7,8,9,10,11]. In a perpendicular magnetic field electrons are trapped around the antidot in a bound state that is formed due to the magnetic confinement. In a classical picture this corresponds to electron skipping orbits around the antidot with a classical cyclotron radius r_c. The operational principle of the proposed device is based on the effect of resonant backscattering from one edge state into another through localized quasi-bound states[6,12,13], combined with the effect of Zeeman splitting of the quasi-bound states in sufficiently high magnetic field.

The geometry of the device is presented in Fig. 1. An antidot is defined in one arm of a quantum wire in a three-terminal geometry. Leads 2 and 3 are kept at the same voltage (e.g. grounded) such that there is no current

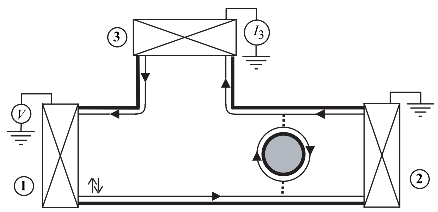

FIG. 1: Schematic geometry of the device. An antidot is defined in one arm of a quantum wire in a three terminal geometry. The wire supports two spin-resolved channels (i.e. the lowest edge state with spin-up and spin-down electrons).

flow between them. We assume that magnetic field is sufficiently high allowing only two spin-resolved channels. The system is described by Hamiltonian $H = \sum_\sigma H_\sigma$, that in the Landau gauge $\mathbf{A} = (-By, 0)$ reads

$$H_\sigma = \frac{\hbar^2}{2m^*}\left[\left(\frac{\partial}{\partial x} - \frac{ieBy}{\hbar}\right)^2 + \frac{\partial^2}{\partial y^2}\right] + V(x,y) + g\mu_B\sigma B (1)$$

where $m^* = 0.067m_e$ is the effective electron mass for GaAs, $V(x,y)$ is the external confining potential. The last term in Eq. (1) accounts for Zeeman energy where $\mu_B = e\hbar/2m_e$ is the Bohr magnetron, $\sigma = \pm\frac{1}{2}$ describes spin-up and spin-down states, $\uparrow, \downarrow$, and the g factor of GaAs is $g = -0.44$. For the case of phase-coherent electron dynamics, the transport through device is described within the Landauer-Büttiker formalism that relates the conductance of the multi-terminal device to its scattering properties[14]. In a sufficiently high magnetic field there is no overlap between the edge states running along opposite sides of the channel, such that $T_{23} = T_{12} = T_{11} = 0, T_{13} = 1$, where T_{ji} defines the transmission probability from lead i to lead j. Define the transmission coefficients of the system as a fraction of electrons that are injected from lead 1 and after being backscattered by the antidot are transmitted into lead 3,

$$T \equiv T_{31}, \tag{2}$$

(note $T_{31} + T_{21} = N$, where the number of spin-resolved channels $N = 2$). Using the Landauer-Büttiker formula we obtain that the current flowing out of the lead 3 is simply determined by the transmission coefficient T

$$I_3 = GV,\ G = \left(e^2/h\right)T. \tag{3}$$

In the absence of the Zeeman term the conductance $G = I_3/V$ would exhibit a series of pronounced peaks whenever the Fermi energy E_F matches the antidot resonant state energies[12]. In the presence of the Zeeman splitting, the energy of each quasibound state is different for electrons of the opposite spins. This leads to the splitting of the corresponding conductance peaks. We thus expect that by varying parameters of the system (e.g. magnetic field, the Fermi energy, the antidot size) the conductance of the device can be tuned within each of the split peaks such that the current in lead 3 will be due exclusively to spin-up or spin-down electrons. Thus, the proposed device can operate as a controllable spin injector. If the incoming state in the lead 1 is already spin-polarized (say, only spin-ups are injected into the lead 1), tuning the energy of the quasibound state to the one corresponding to spin-down electrons would suppress the current completely, i.e. the device would operate as a spin filter or switcher.

In order to test feasibility of the proposed device we perform full quantum mechanical transport calculations for the case of an antidot system defined in GaAs heterostructure. In order to calculate the transmission coefficient we use the "hybrid" recursive Green function technique (the details of the method can be found in[15]). We use the model of a hard wall confinement to approximate the potential profile of the antidot and the wire. This is certainly a simplification in comparison to the actual smooth potential profile in the device. This model is however fully sufficient for the present purposes because in the one-electron picture the use of the smooth instead of the hard wall confinement would only change a position and a width of the conductance peaks, but would not affect the main features of the conductance.

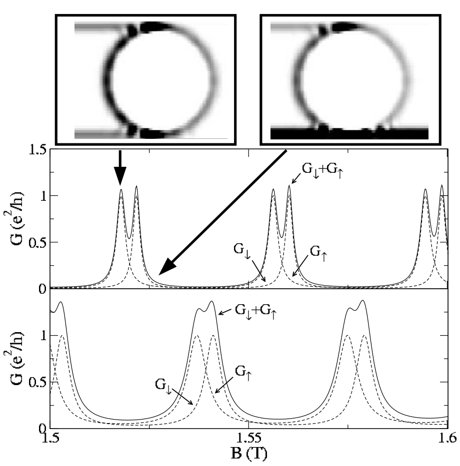

FIG. 2: The conductance of the device $G = I_3/V$ as a function of perpendicular magnetic field B. The middle and lower panels correspond to the cases of weak and strong coupling where the antidot diameter is $d = 318$ nm and $d = 320$ nm respectively. The width of the wire $w = 400nm$, and the sheet electron density $n_s = 10^{15}m^{-2}$. The upper panel shows the current density for spin-up electrons for the resonant and off-resonant transmission.

Figure 2 shows the three-terminal conductance of the device $G = G^{\uparrow} + G^{\downarrow}$ as a function of magnetic field, where $G^{\uparrow}$ and $G^{\downarrow}$ represent the conductance of the individual spins channels given by Eq. (3). The conductance $G = G(B)$ exhibits periodic oscillations, where the periodicity (i.e. the distance between two pairs of the split peaks) is related to the addition of one flux quantum $\phi_0 = h/e$ to the total flux $\Phi = BS$ (S being the area of the antidot). This gives $\Delta B = h/eS = 0.04$T which is consistent with the calculated periodicity $\Delta B = 0.05$T (note that the area enclosed by the bound state is larger than S because of the finite spatial extend on the wave function). In the upper panel of Fig. 2 we illustrate the effect of resonant backscattering via the quasibound antidot state by plotting the current density plots for the cases of on- and off-resonant transmission. It is worth mentioning that the operation of the device is conceptually similar to add-drop filters and mode couplers in quantum optics and optical communications[16].

The broadening of the peaks in each pair is determined by the coupling strength between the bound state and the edge states. This is illustrated in Fig. 2 for the cases of weak and strong coupling where two peaks in each pair are respectively separated or practically merged. By decreasing the coupling strength the peaks can be made sufficiently narrow such that the efficiency of the spin injection (that we define as $\xi = 2|G_{\uparrow} - G_{\downarrow}|/(G_{\uparrow} + G_{\downarrow})$) can theoretically reach 100%. In practice this value may be reduced by e.g. temperature broadening, asymmetry in coupling to upper and lower edge states etc. For a given magnetic field the spitting of the peaks is determined by the g-factor of the material and thus can not be changed. We note with this respect that utilization of the material with higher g factor, e.g. InAs where $|g| = 15$ will apparently lead to much more pronounced peak splitting and thus higher efficiency ξ.

Consider now two three-terminal devices connected in series as shown in Fig. 3. The edge state leaving the device 1 and entering the device 2 is not reflected back to the device 1 (it can leave through leads 3 or 4 only). Since multiple reflections between two devices are absent, the transmission coefficient T_{31}^{4t} in a four-terminal geometry is simply given by the sum $T_{31}^{4t} = T_1^{\uparrow}T_2^{\uparrow} + T_1^{\downarrow}T_2^{\downarrow}$, where $T_1^{\uparrow(\downarrow)}$ and $T_2^{\uparrow(\downarrow)}$ are the transmission coefficients of individual devices 1 and 2 for spin-up (spin-down) states defined by Eq. (2) (note that we neglect spin-flip processes such that two spin channels are totally independent).

Let us now illustrate the operation of the device as a spin filter or spin switcher. Consider the geometry of Fig. 3 (two devices connected in series). Assume that parameters of the device 2 can be independently changed, for example by a back gate that varies locally the electron density n_s. The transmission coefficient T_2 exhibits a series of split peaks as a function of n_s, see inset to Fig. 3. Assuming that leads 2 - 4 are grounded and applying Landauer-Büttiker formalism we obtain for the four-terminal conductance $G^{4t} = I_3/V = T_{31}^{4t}V$, where I_3 is the current out of lead 3 and V is the voltage at lead

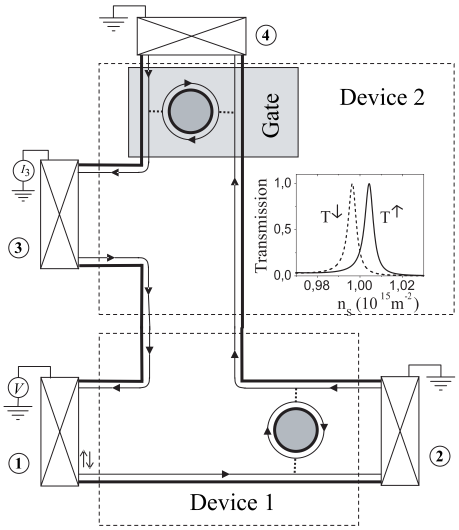

FIG. 3: Two antidot devices connected in series. A back gate at device 2 varies locally the electron density n_s. The inset shows the transmission coefficient $T = T^{\uparrow} + T^{\downarrow}$ of a single device as a function of the sheet electron density $n_s = k_F^2/2\pi$ for the wire of the width $w = 400$ nm and the antidot diameter $d = 318$ nm, $B = 1.52$ T.

1. Suppose that magnetic field is tuned such that only one spin polarized state (say spin-up) passes the device 1 and enters the device 2, i.e. $T_1^{\downarrow} = 0, T_1^{\uparrow} = 1$. In this case $T_{31}^{4t} = T_1^{\uparrow}T_2^{\uparrow} + T_1^{\downarrow}T_2^{\downarrow} = T_2^{\uparrow}$. Thus, by varying the back gate voltage, one can adjust $T_2^{\uparrow}$ such that the spin-up state entering the device 2 is either totally transmitted or blocked. Therefore, the proposed device operates as a controllable filter/switch for incoming spin-polarized electrons.

We would like to stress that in our calculations we used a one-electron Hamiltonian where electron-electron interaction is effectively included in form of an external self-consistent potential. This one-electron description was successfully used to explain various features observed in a number of experiments on antidot structures[6,9,13]. It has been argued however that charging effects may be important for understanding of such features in the conductance as double-frequency ($h/2e$) AB oscillations[8,10,11]. As magnetic field increases, the conductance peaks/dips (of the periodicity $\Delta BS = h/e$ discussed above) split into pairs, which was usually taken as the signature of Zeeman induced spin splitting. As B increases further, the splitting saturates such that peaks/dips become equidistantly spaced (i.e. the oscillations become $h/2e$-periodic). This effect was explained in[10] in terms of charging of compressible regions (CR) forming around antidots. Within this model the conductance peaks/dips are due to electrons of the same spin tunnelling through the outer spin states. It was however noted[10] that it is unclear whether CR really exist at low B and it was suggested that a gradual transition from conventional Zeeman splitting to the interacting picture may take place as B increases. Thus the detailed nature of $h/2e$ oscillations still remains an open question and its full understanding requires accounting for spin and charging effect in a self-consisted way. We currently undertake full quantum-mechanical transport calculation combined with the local-spin-density approximation in an attempt to answer this question. Note that two antidot devices in series (functioning as a spin filter/switch as described above) can be used to test whether the $h/2e$ oscillations are due to electrons of the same or different spins.

To conclude, we suggest an antidot-based device that can inject and control spin-polarized current. We hope that the present paper will stimulate further interest to quantum antidot systems which provide a powerful tool to study, control and manipulate the spin degrees of freedom of electrons.

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